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DESIGN AND CONSTRUCTION OF TRUCK ARRESTER BED RESEARCH FACILITY.

The Pennsylvania State University

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Design and Construction of a Truck Arrester Bed Research Facility

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Finally, I am grateful for the support and encouragement given by my wife, Karen, and our children, Jonathan, Matthew, Heather, and Brian. This report is dedicated to them.

ABSTRACT

During the summer of 1984, an Arrester Bed Research Facility was constructed adjacent to the Pavement Durability Research Facility of the Pennsylvania Transportation Institute. The Arrester Bed Research Facility is to be used for experimentation in the mechanism of stopping runaway vehicles with escape ramps. The results of the study will be empirically-substantiated criteria for the design of highway escape ramps. This report is the first segment of a paper which will include descriptions of 1) construction of the arrester bed, 2) experiments performed, 3) analysis and presentation of results, and 4) recommended design criteria. Specific items covered in this first report are 1) background information, 2) design description, 3) construction phase elements, and 4) work sampling studies and productivity reports.

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INTRODUCTION

This report describes the construction phase of the Arrester Bed Research Facility of the Pennsylvania Transportation Institute. As a preliminary, some background information is provided which discusses the need for such a facility. Next, the track design is explained. A project description is included with a daily account of construction progress. During the course of the project, three major operations (excavation, fine-grading, and pipe-laying) were analyzed in detail. The results of the studies are included as separate chapters.

BACKGROUND

On highways with long, steep down-grades, heavy vehicles such as trucks and tractor-trailers occasionally lose their braking capabilities, and become so-called runaway trucks. These vehicles, if not properly stopped, can cause loss of life and extensive property damage.

Efforts have been made in the last twenty years to solve the problems associated with stopping runaway vehicles. Usually, truck escape ramps with beds of gravel, sand, or dirt have been built near the road. Trucks may be driven into the beds and stopped by the grade and drag forces of the beds. Although some other methods have been suggested (such as chain arrester systems and hydraulic arrester systems), the escape ramp is the most effective means of stopping runaway trucks. It is believed that the gravel-filled arrester bed (followed by the sand pile and then the gravity ramp) is the most effective type of escape ramp. Of the three types of ramps, the gravity ramp is usually the most expensive, then the gravel arrester bed, with the sand pile being the least expensive. The gravel arrester bed, considering its cost and performance, is the most cost-effective ramp. The maintenance of truck escape ramps costs very little compared to other options for stopping runaway vehicles.

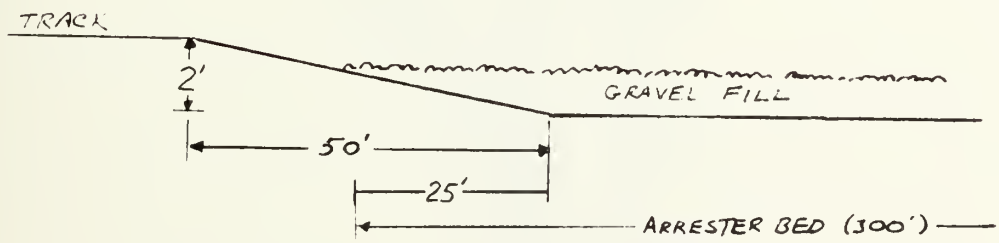
However, the fundamental understanding of the mechanisms involved in stopping runaway vehicles is limited, and does not yet yield precise specifications for design. Field testing has been done primarily to evaluate the performance of a specific ramp rather than to extend basic knowledge. A microscopic study of the stopping mechanisms has never been performed to analyze the relationship between drag force and its related factors.

It has been recommended that research be undertaken to improve the understanding of the mechanism of stopping runaway vehicles by escape ramps, so that adequate design can be achieved, and overdesign avoided. In particular, the relationship between the drag force and its related factors (vehicle speed, contact pressure, tire size, gravel size, etc.) must be determined so that a formula can be provided for design engineers to use in computing the required length for an escape ramp.

Long-term performance of the escape ramp has not been studied. Such monitoring might answer questions such as the percentage of fine material that would require replacement, the service life of the gravels used in the arrester beds, and the relationship of service life to frequency of use.

The Arrester Bed Research Facility (ABRF) is in essence a paved, 900-foot, straight track. As shown in Figure 1, a tangent to the right-hand side of the Pavement Durability Research Facility (PDRF) serves as the centerline of the ABRF. The PDRF provides a 1000-foot straight run for a vehicle to attain the desired speed, and stabilize prior to entering the ABRF.

At the 150-foot mark, the approximate point of entry onto the track, the roadwidth is 18 feet. Continuing straight ahead, a vehicle will approach arrester bed #1. The bed is two feet deep, twelve feet wide, and stretches from the 450-foot mark to the 750-foot mark. Depending on the test in progress, the bed will be filled with varying grades of crushed gravel or rounded, river gravel. At the 425-foot mark, the blacktop will begin a 3 percent slope down to the depth of the bed, ending 25 feet into the bed. The slope will be covered with gravel to a level even with the top of the bed (see below). The floor of the bed is not paved, but is simply the compacted clay of the subgrade. As the vehicle proceeds along the track, it will pass, on its left, a 2:1 slope which rises between six and ten feet. At the end of the bed is a short, inclined roll-off area. However, it is not anticipated that a vehicle will actually ever reach the end of the bed.



To use arrester bed #2, a vehicle will, upon entering the track, angle slightly to the right. Passing bed #1 on its left, the vehicle will, at approximately the 500-foot mark, angle back to the left and straighten up. The usable track width is approximately twelve feet. The pavement will begin a 3 percent slope at the 775' mark, and, again, will be covered with gravel to

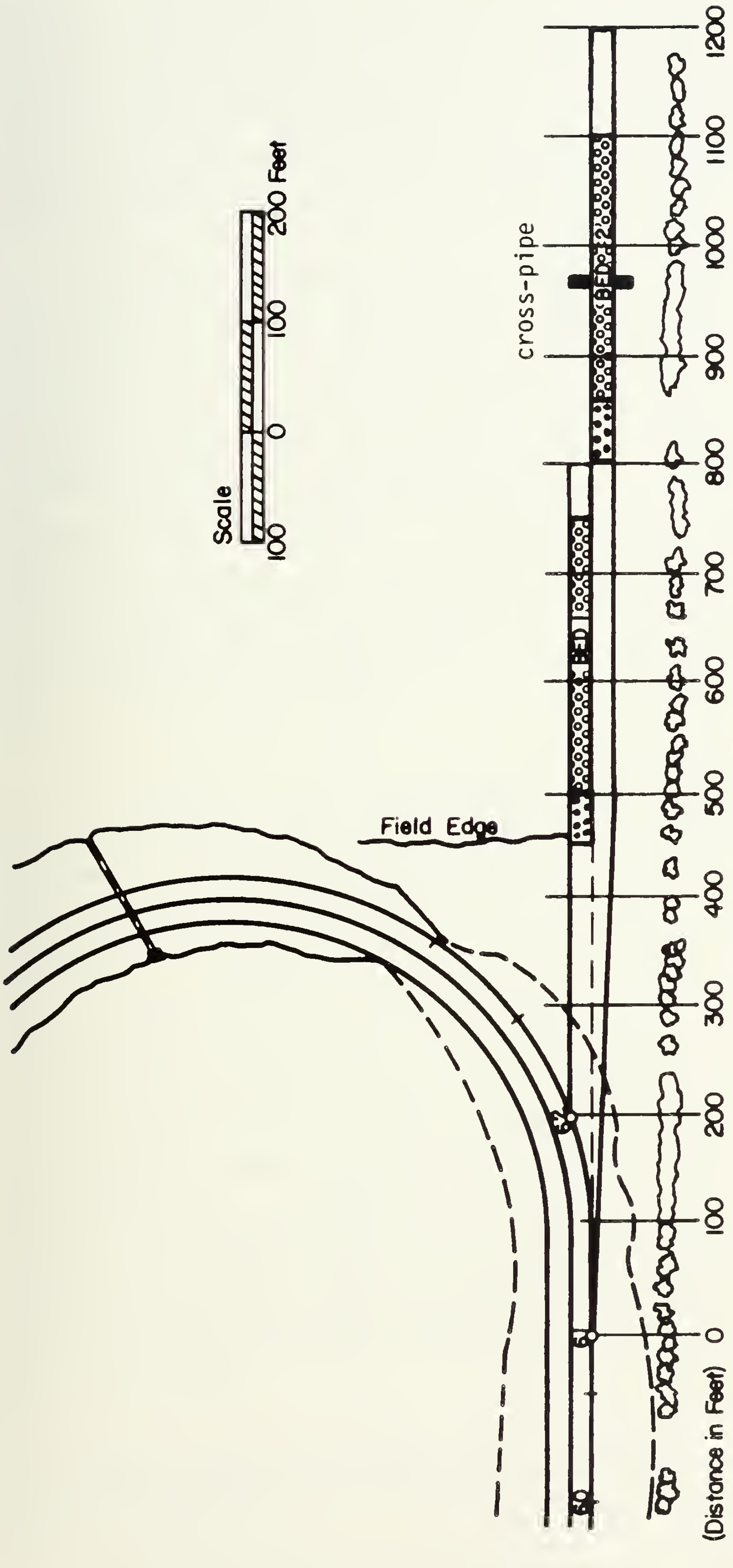

Scale
100
0
100
200 Feet
cross-pipe
BED 2
BED
Field Edge
(Distance in Feet)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

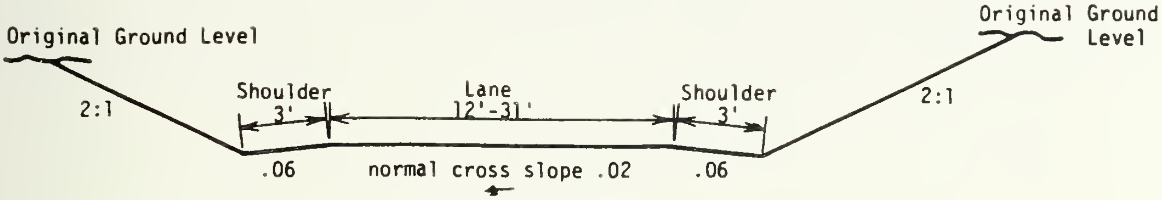
Figure 1.

the same level as that in the bed. At the 800-foot mark, the vehicle will be directly over the front of the bed. Like bed #1, bed #2 is twelve feet wide, two feet deep, and three hundred feet long. It also ends with a slightly inclined roll-off area. The cut on the right side of the track, though in higher ground than that on the left, was also left with a 2:1 slope.

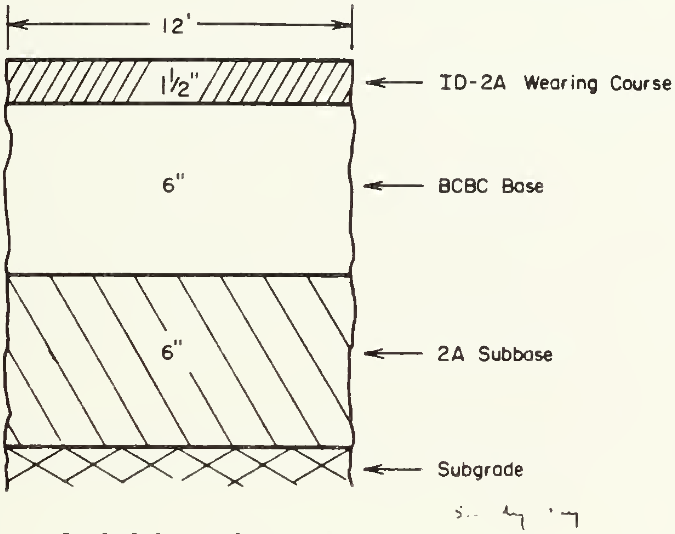
The area in which the track is situated was formerly used as a corn field, and the ground had a slight downward slope from right to left. Since the track, level in the longitudinal direction, was cut out of high ground (to bring it to the same elevation as the straightaway of the PDRF), drainage of rainwater required special consideration. On the left side of the track, from the 200-foot mark to the 800-foot mark, is a 1 1/2-foot deep, 15 inch wide, drainage ditch. The ditch is lined with a synthetic felt, contains a 4-inch, perforated, plastic drain pipe, and is backfilled with 2B crushed gravel. The track and bed #1 are tilted slightly to direct runoff into the drain. The drain empties into a natural, low area around the 950-foot mark and dissipates down the slope to the left.

The low area, a natural drainage path from right to left, centered at about the 950-foot mark, had to be filled in (to keep the track horizontal). In order to allow the natural drainage to continue, a 21-inch concrete cross-pipe was installed under bed #2. Ten four-foot sections of pipe (with unsealed joints) were placed in a 2 1/2-foot wide by 3-foot deep trench, and the trench was then backfilled with 2B gravel. The bed is sloped slightly from both ends so that water will be channelled to the cross-pipe trench. Water falling outside the bed, to the left, will run down the slope and follow the same path as that discharged by the cross-pipe. Water falling on the right side will enter a swale which starts at the 750-foot mark, and be channelled to the high side of the cross-pipe. Except for a low, continuous mound to contain the gravel, the ground on either side of bed #2 slopes down and away; on the left side, the ground slopes down to the existing slope of the field, and, on the right side, the ground slopes into the swale which was cut for drainage.

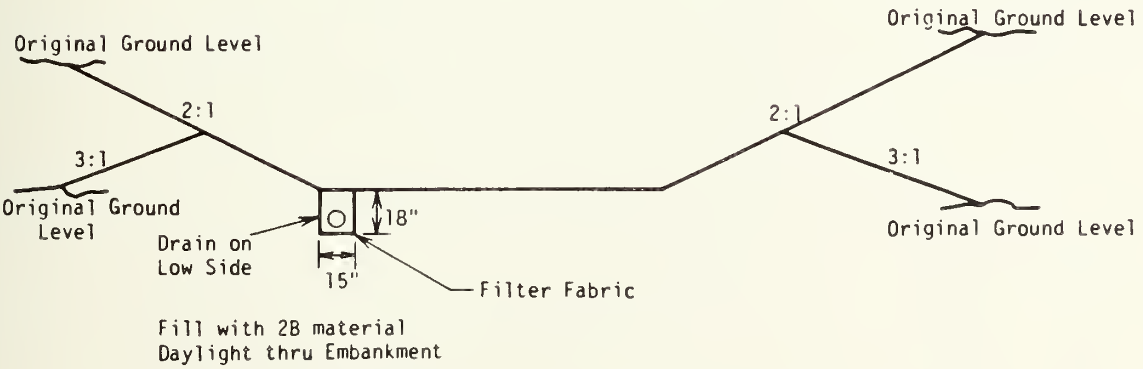
Figure 2 shows the typical cross-section of the road, the pavement, and arrester bed #1.



TYPICAL ROAD CROSS-SECTION



PAVEMENT CROSS-SECTION



TYPICAL ARRESTER BED CROSS-SECTION WITH DRAINAGE SYSTEM

Figure 2.

Finally, there must be a means of extracting the vehicles from the arrester beds. Approximately 100 feet before the start of each bed, there will be a concrete deadman. It is intended that test personnel will be able to anchor some sort of mobile winch to the deadman (otherwise covered by a steel plate) which will pull the vehicles backward until they can back up under their own power.

PROJECT DESCRIPTION

The purpose of this project was to provide the Pennsylvania Transportation Institute with a means of investigating the mechanism of stopping runaway trucks on escape ramps. The construction involved several work elements which were performed essentially during July and August of 1984. The result is the Arrester Bed Research Facility. This section is a report and daily account of the observed progress of the operation.

The writer made his first observation of the worksite on Wednesday, 20 June. The site was a rolling cornfield. At the edge of the Pavement Durability Research Facility, the ground rose six to ten feet. Approximately 800 feet away, in the planned path of the track, the ground dipped into the low area. This low area was the natural drainage path from higher fields on the right to the lower fields on the left. Along the right side, 20-30 feet away, is a line of full-grown trees. On the following day, 21 June, a Caterpillar D8H dozer was moved to the site, and, during the following week, a survey crew placed elevation markers and centerline markers along the planned path of the track. However, the first full day of construction work was 29 June.

6/29 Friday - Today, the D8H was used to strip the topsoil from the track. The topsoil was pushed into a row along the right side of the track. Also, a spoil area has been cleared at about the 700' mark on the left side of the track.

6/30 - 7/1 Weekend - Heavy rain saturated the exposed clay.

7/2 Monday - The ground was too wet to work. No on-site activity today.

7/3 Tuesday - D8 began operation at 7:30 am, pushing still-wet clay along the path to the low area. At 10:35, the D8 was stopped for track cleaning, and oil leak repairs. By 2:15, the repair operation was still in progress.

7/4 Wednesday - Holiday (no work).

7/5 Thursday - A Caterpillar 631B scraper was brought to the site. The only work in progress was the D8 pushing clay along the track. A surveyor was at the site to check the slopes of the developing side banks. The clay was too moist at this time to use the scraper.

7/6 Friday - no work today.

7/7 - 7/8 Weekend.

7/9 Monday - The scraper and dozer were operating in tandem to excavate clay from the track. The clay was being dumped in the spoil area and was being compacted by a sheep's-foot roller.

7/10 Tuesday - The scraper, dozer, and roller were operating as they were yesterday. The track elevation was dropping steadily. The banks were being checked periodically by the surveyor (who is otherwise operating the roller), and are being maintained at a 2:1 slope.

7/11 Wednesday - The dozer, scraper, and roller were in operation again. The track was close to subgrade level, and the low area at the 950-foot mark was filling in.

7/12 Thursday - The dozer was the only equipment in operation today. It was being used to smooth out the piled clay in the waste area and fill in the low area.

7/13 Friday - Same as yesterday. The compactor has rolled the entire track; the dozer has spread the excess clay across the waste area, and covered it with topsoil.

7/14 - 7/15 Weekend.

7/16 Monday - No activity today.

7/17 Tuesday - No activity today. Apparently we are waiting for equipment to be "freed up" from other jobs. A backhoe is required to dig a trench for a crosspipe. Also, two large piles of 2B gravel have been delivered along with the ten 4-foot sections of the crosspipe. The material has been placed off of the track, but in the general area of planned installation.

7/18 Wednesday - Heavy rain last night; no activity today.

7/19 Thursday - Backhoe on site. The only activity today was the three-man operation to dig the trench and install the crosspipe (with 2B backfill).

7/20 Friday - A Caterpillar D3B dozer was used to fine-grade the track prior to rolling. A smooth-wheeled compactor rolled the first half of the track. A small section of the bank (on the right side at the entrance to the track), which would have blocked a truck driver's view from the PDRF approach lane, was removed.

7/21 - 7/22 Weekend.

7/23 Monday - The D3 dozer was used to begin cutting in the two arrester beds.

7/24 Tuesday - Same activity as yesterday. Also, swales for drainage on both sides of bed #2 have been cut in. A "stone box" (for laying subbase) has been brought to the site.

7/25 At 9:30 am, truck loads of 2A gravel subbase began arriving. The "stone box" was being used in conjunction with the dump trucks to lay a 12-foot wide, 8" deep subbase. The operation was observed until noon. Five dump trucks were used, and each made round trips (approximately one hour in duration) to a loading site in Bellefonte. There was often a delay between dump trucks (up to

20 minutes). The average operating time of the stone box (each time a load of gravel was delivered) was 31 seconds. Over the ten observed cycles, which spanned 1 hour-46 minutes, the "stone box" and operator were being used productively less than 5% of the time. Behind the "stone box", a smooth roller was compacting the subbase. It probably would have been more efficient for the "stone box" operator to operate the roller during his 95% "free time."

7/26 Thursday - Trench operation. Two men, one operating the backhoe, were digging the trench for the drainpipe along the left side of the track. The felt wrap, 4-in. plastic pipe, and 2B gravel backfill were all on the site.

7/27 Friday - Rain. No activity.

7/28 - 7/29 Weekend.

7/30 Monday - The trenching operation was still in progress. There was no other activity at the site.

7/31 Tuesday - The trenching operation was completed. The felt liner and plastic drain pipe were installed, and backfilled with the 2B.

8/1 Wednesday - A Caterpillar 14E road grader was brought to the site to taper the subbase into the beds. The taper is a 3% slope starting 25 feet before the beds, and ending 25 feet into them. The rest of the subbase was moistened with a watering truck, fine graded with the grader, and rolled. Today was the last day of the writer's on-site observations.

8/ The paving operation commenced.

8/ The deadmen were installed.

8/ Construction has been completed and signed off. The Arrester Bed Research Facility is now ready for use.

As this report is being written, the only work remaining is the installation of two end sections on the concrete crosspipe, paving, and the installation of a concrete deadman in front of each bed. The end sections may be installed within the next couple of days. Depending on the contractor's paving schedule, the paving will be accomplished within the next two weeks. After the paving, the deadmen will be installed. At that point in time, the contractor will deliver different types of gravel for the arrester beds, and the Arrester Bed Research Facility will be ready for use.

SCRAPER OPERATION STOPWATCH STUDY

SCRAPER OPERATION STOPWATCH STUDY

A stopwatch study was conducted during the excavation segment of the project. The excavation was accomplished primarily with the use of a Caterpillar 631B scraper on 9 and 10 July, and required the removal of approximately 5000 cubic yards of sandy clay. The purpose of the study was to determine average cycle time, average cycle element times, and delay time. The cycle consisted of four elements: 1) the scrape (picking up dirt), 2) the run to the waste area, 3) the dumping of material, and 4) the return trip. The scrape started when, with the assistance of a pusher, the scraper began to cut into the dirt. The run started when the scraper lifted its blade, and began moving under its own power. The dump started when the gate on the front of the barrel was lifted. Finally, the return trip started when the gate was dropped, and ended when the new scrape began. The duration of the observation period was approximately six hours. During this period, 63 cycles were recorded. Table 1 presents a compilation of all recorded cycle element times. The four missing cycle element times resulted from incorrectly recorded stopwatch times, and were excluded from subsequent calculations and analysis. The table also shows the resultant means and standard deviations of the full cycles and cycle elements. Finally, the table shows the amount of delay/break time during the observation period.

It was desired that the data be presented in graphical form (histograms). In order to accomplish this task, the distributed data for each cycle element and for the full cycle were divided into discrete classes (see Tables 2 through 6). The classes were chosen to be small enough in range to present a reasonable picture of the data distribution. (See Figures 3 through 7.) Except for the Dump Time Histogram, which is somewhat skewed to the right, the histograms generally show the typical shape of the standard distribution.

Figure 8 shows the cumulative relative distribution of the full cycles and the cycle elements. Those curves with the more vertical slopes (scrape and run) represent elements with more consistent durations. The lesser slopes of the other two cycle elements may be simply explained. The observer was positioned directly beside the scrape area. The start and stop of the

Table 1. Scraper operation cycle times (seconds).

Cycle	Scrape	Run	Dump	Return	Total	Cycle	Scrape	Run	Dump	Return	Total
1	50	65	60	85	260	33	62	78	30	113	283
2	--	55	100	--	285	34	77	81	35	129	322
3	62	55	105	133	355	35	56	72	26	153	307
4	55	55	95	100	305	36	61	59	37	134	291
5	52	70	98	100	320	37	53	67	26	137	283
6	65	80	55	235	435	38	42	67	45	123	277
7	60	83	65	85	293	39	60	66	27	123	276
8	50	125	92	110	377	40	52	68	32	134	286
9	55	82	83	130	350	41	56	62	32	128	278
10	67	57	105	96	325	42	58	67	41	130	296
11	58	75	60	162	355	43	50	58	24	64	196
12	86	70	18	116	290	44	49	63	95	146	353
13	63	69	81	145	358	45	55	65	33	112	265
14	60	82	53	152	346	46	85	65	38	86	274
15	68	64	73	125	330	47	52	65	48	122	287
16	55	84	47	112	298	48	52	67	37	126	292
17	67	71	52	131	321	49	54	64	17	118	253
18	67	83	43	131	324	50	64	75	34	121	294
19	69	65	58	205	392	51	44	74	43	151	312
20	69	80	36	154	339	52	62	73	21	127	283
21	61	57	37	144	299	53	49	73	34	177	331
22	63	81	40	196	380	54	46	64	25	137	272
23	72	73	79	143	367	55	52	60	29	147	288
24	59	88	60	147	354	56	51	67	36	108	262
25	66	63	69	--	--	57	52	60	42	127	281
26	67	78	42	170	357	58	43	61	27	114	245
27	65	76	45	182	368	59	47	65	23	135	270
28	65	63	53	135	316	60	47	51	21	162	281
29	60	83	30	154	327	61	49	65	20	130	264
30	60	72	58	220	410	62	49	47	26	176	298
31	73	83	62	157	375	63	60	63	33	167	323
32	80	67	67	173	387						

Cycle Element	Mean ($\overline{x}$)	Std. Dev. (σ)
Scrape	59.7	11.2
Run	69.6	11.5
Dump	48.5	23.9
Return	135.8	34.6
Total	313.6	39.8

- Total sum of cycle times 5 hrs. 8.4 min.
- Observation period 6 hrs. 11.0 min.
- Delay time 45.1 min.
- Break time 17.5 min.

Average of 1 minute of delay every 6.8 minutes of work.

Table 2. Frequency table for scrape time.

Class No.	Class Limits	Class Mid-Point	Absolute Class Freq.	Relative Class Freq.	Upper Class Limit	Cum. Abs. Freq.	Cum. Rel. Freq.
1	40-50	45	10	16.1	50	10	16.1
2	50-60	55	21	33.9	60	31	50.0
3	60-70	65	25	40.3	70	56	90.3
4	70-80	75	3	4.8	80	59	95.1
5	80-90	85	3	4.8	90	62	100

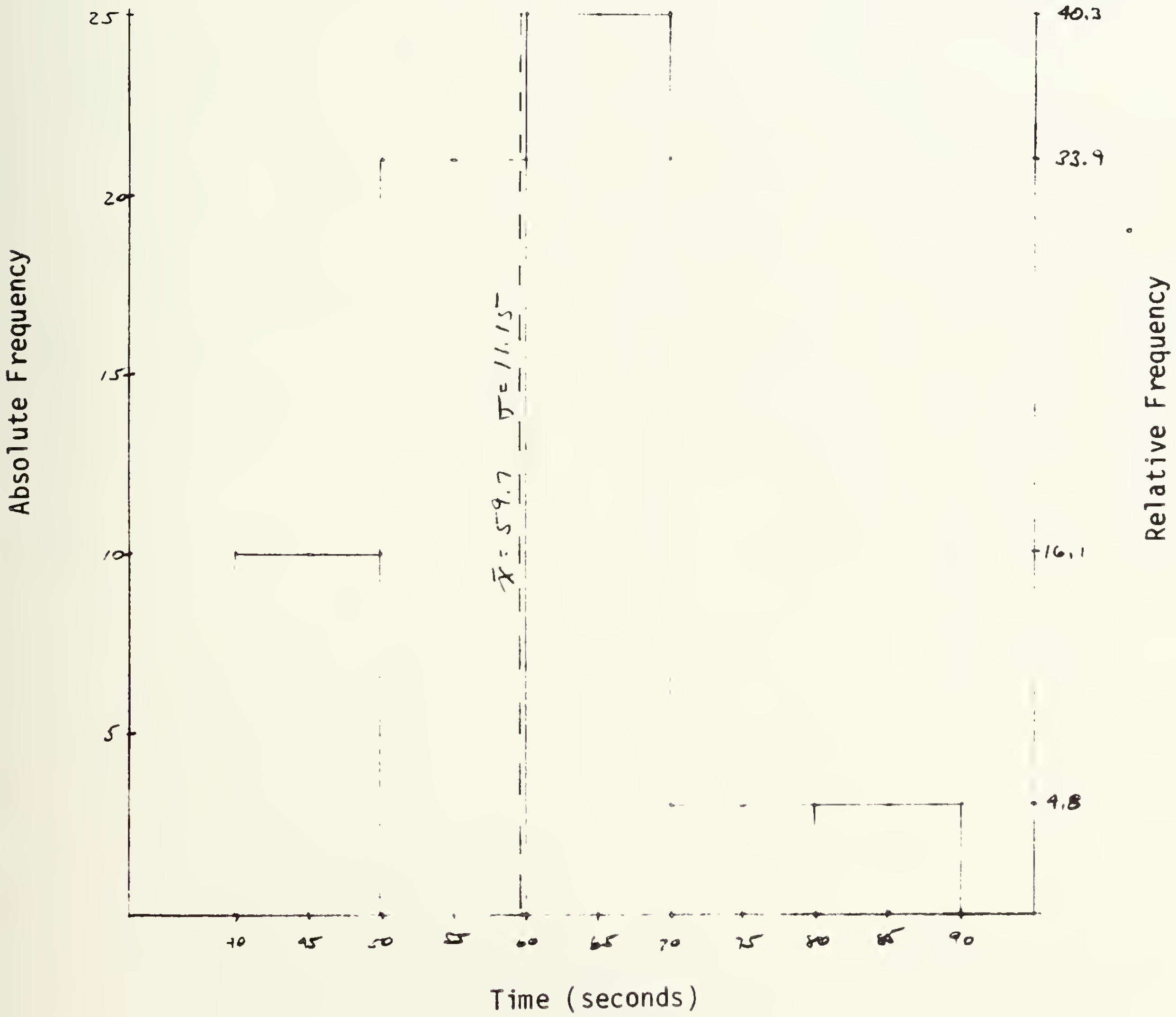


Figure 2. Relative frequency histogram of scrape time.

Table 3. Frequency table for run time.

Class No.	Class Limits	Class Mid-Point	Absolute Class Freq.	Relative Class Freq.	Upper Class Limit	Cum. Abs. Freq.	Cum. Rel. Freq.
1	40-50	45	1	1.6	50	1	1.6
2	50-60	55	8	12.9	60	9	14.5
3	60-70	65	27	43.5	70	36	57.0
4	70-80	75	14	22.6	80	50	79.6
5	80-90	85	12	19.4	90	62	100

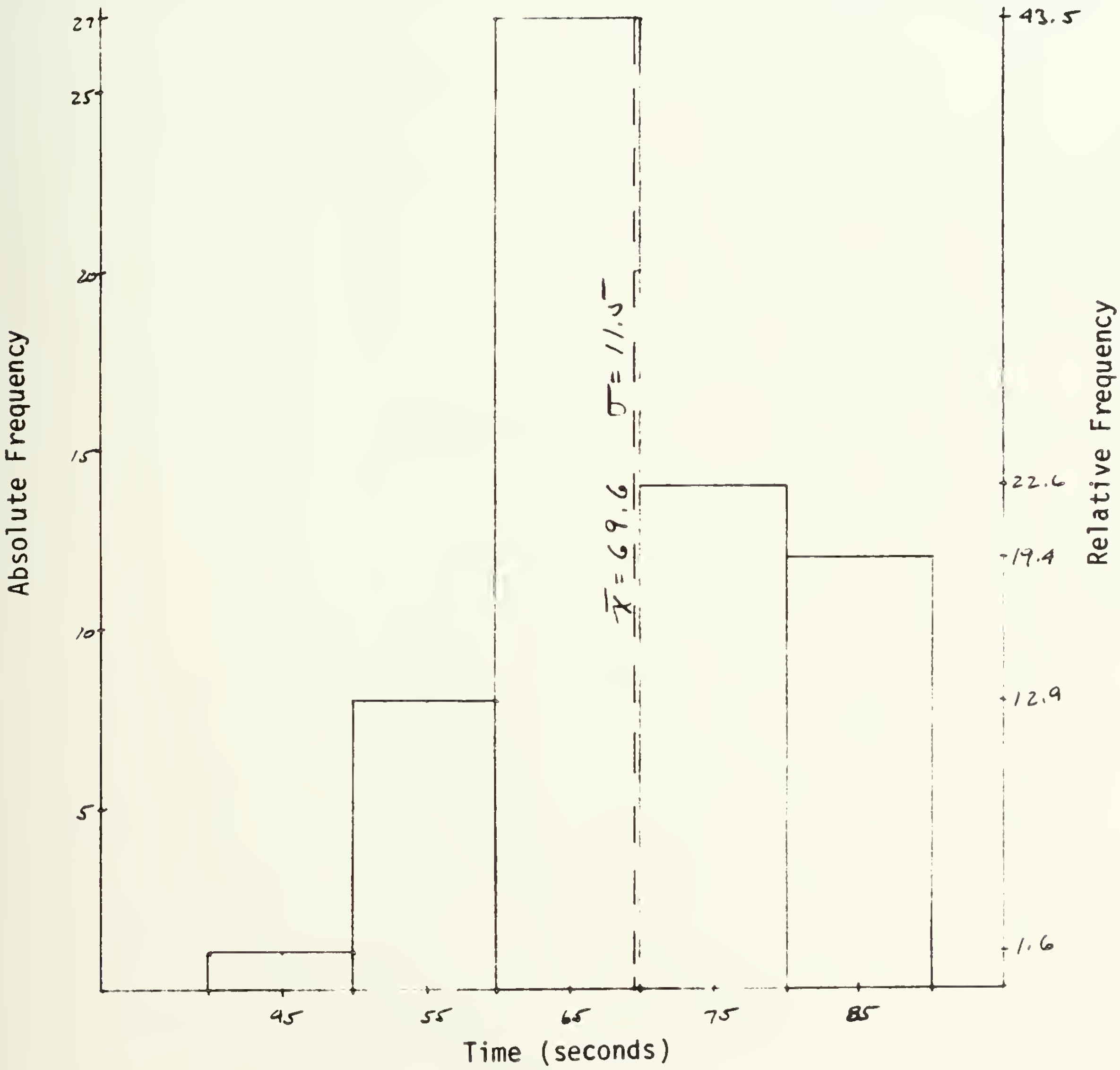


Figure 3. Relative frequency histogram of run time.

Table 4. Frequency table for dump time.

Class No.	Class Limits	Class Mid-Point	Absolute Class Freq.	Relative Class Freq.	Upper Class Limit	Cum. Abs. Freq.	Cum. Rel. Freq.
1	0- 20	10	2	3.2	20	2	3.2
2	20- 40	30	27	42.9	40	29	46.0
3	40- 60	50	16	25.4	60	45	71.4
4	60- 80	70	9	14.3	80	54	85.7
5	80-100	90	6	9.5	100	60	95.2
6	100-120	110	3	4.8	120	63	100

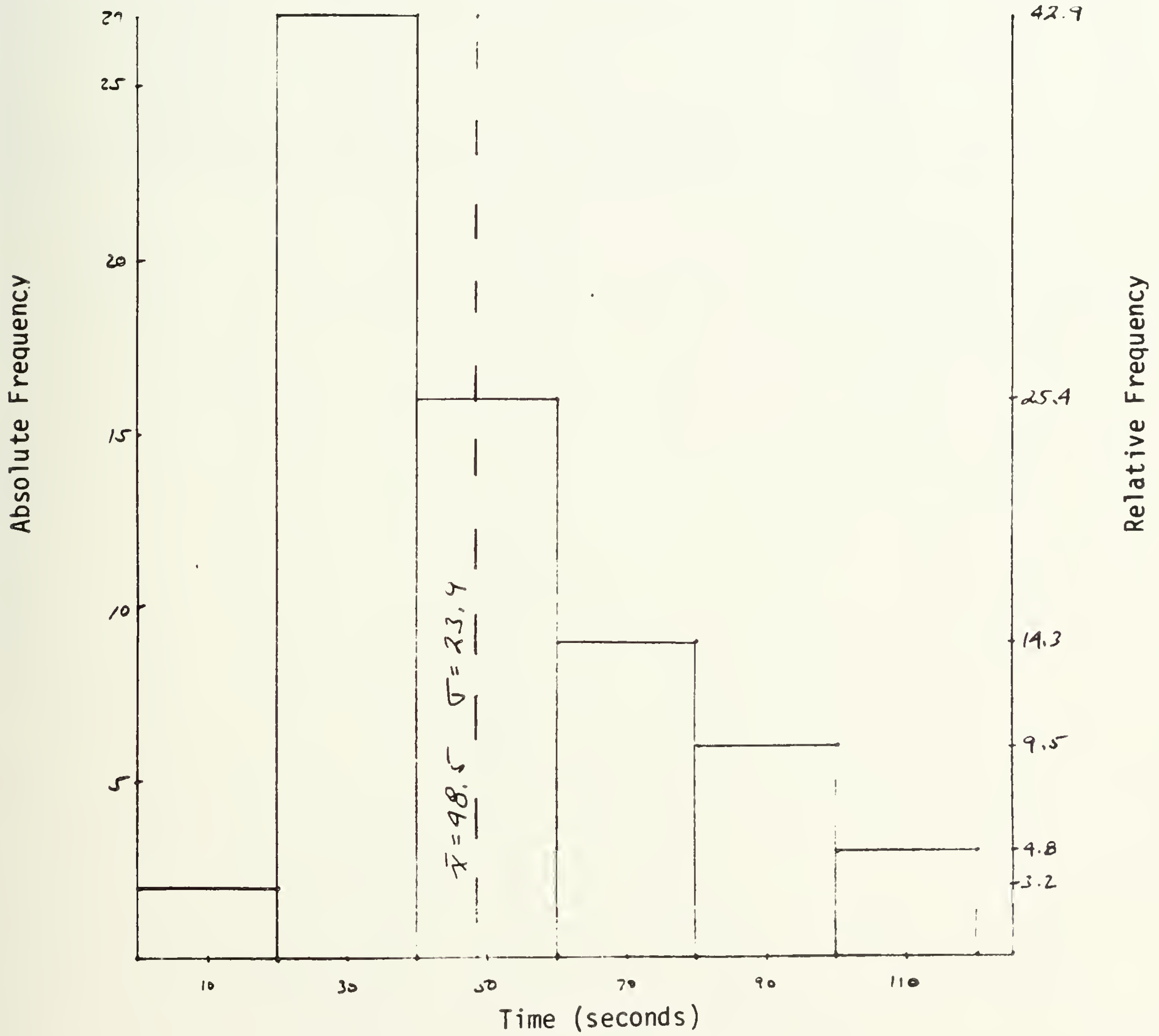


Figure 4. Relative frequency histogram of dump time.

Table 5. Frequency table for return time.

Class No.	Class Limits	Class Mid-Point	Absolute Class Freq.	Relative Class Freq.	Upper Class Limit	Cum. Abs. Freq.	Cum. Rel. Freq.
1	60- 80	70	1	1.6	80	1	1.6
2	80-100	90	4	6.6	100	5	8.2
3	100-120	110	10	16.4	120	15	24.6
4	120-140	130	22	36.1	140	37	60.7
5	140-160	150	12	19.7	160	49	80.3
6	160-180	170	7	11.5	180	56	91.8
7	180-200	190	2	3.3	200	58	95.1
8	200-220	210	1	1.6	220	59	96.7
9	220-240	220	2	3.3	240	61	100

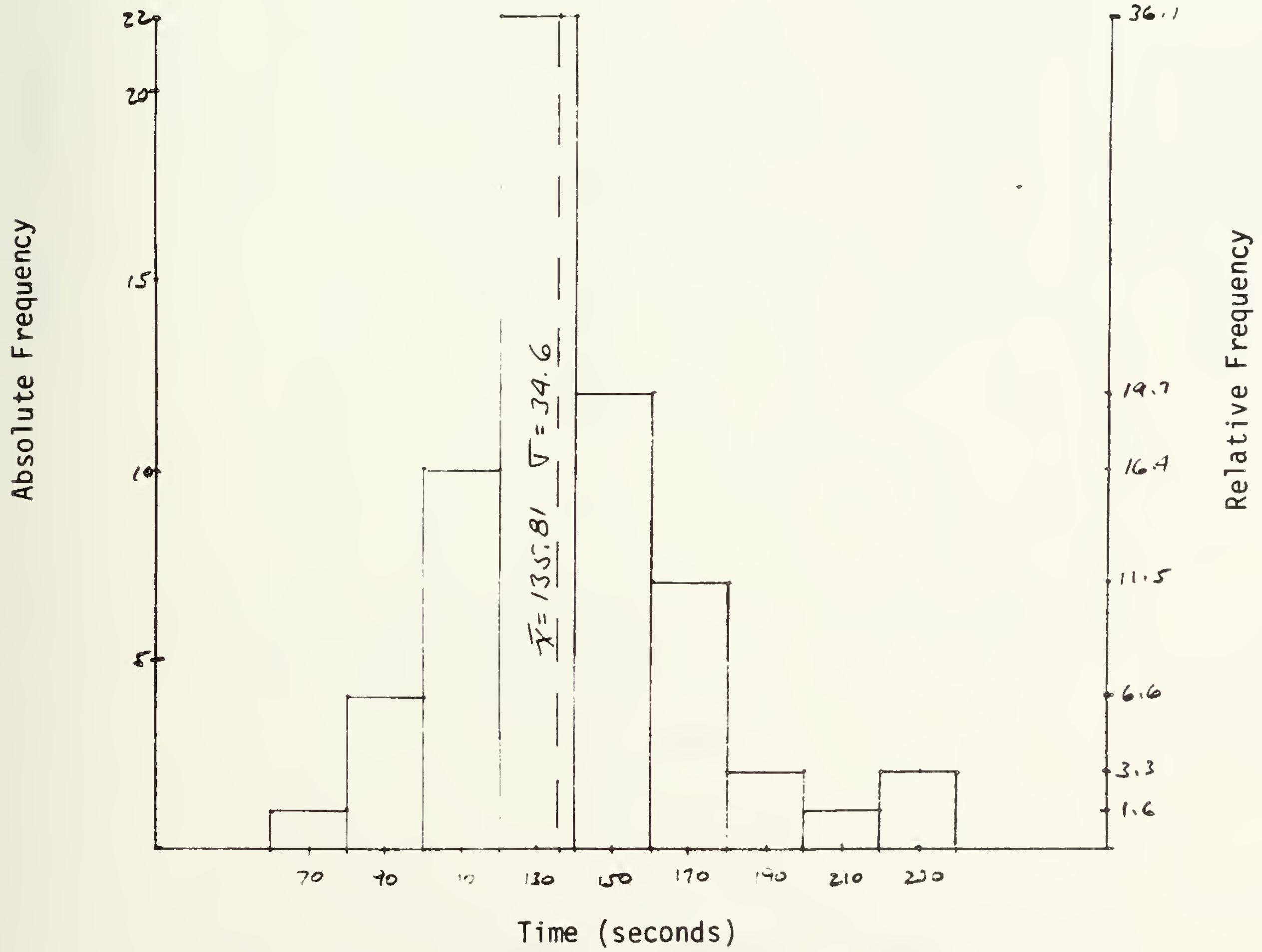


Figure 5. Relative frequency histogram for return time.

Table 6. Frequency table of total cycle times for scraper operation.

Class No.	Class Limits	Class Mid-Point	Absolute Class Freq.	Relative Class Freq.	Upper Class Limit	Cum. Abs. Freq.	Cum. Rel. Freq.
1	220-250	235	1	1.7	250	1	1.7
2	250-280	265	11	18.6	280	12	20.3
3	280-310	295	19	32.2	310	31	52.5
4	310-340	325	12	20.3	340	43	72.9
5	340-370	355	10	16.9	370	53	89.8
6	370-400	385	5	8.5	400	58	98.3
7	400-430	415	1	1.7	430	59	100

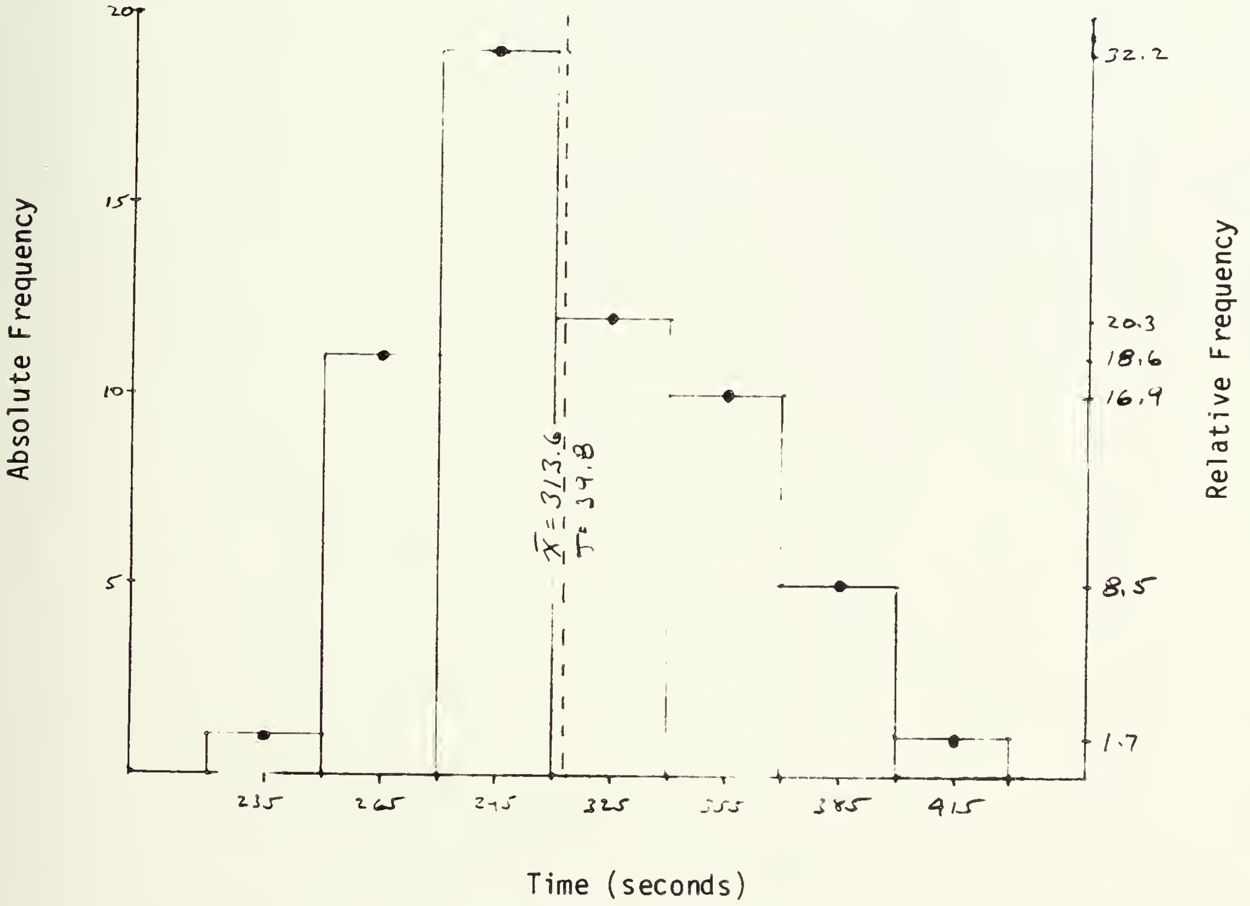


Figure 6. Relative frequency histogram for total cycle times.

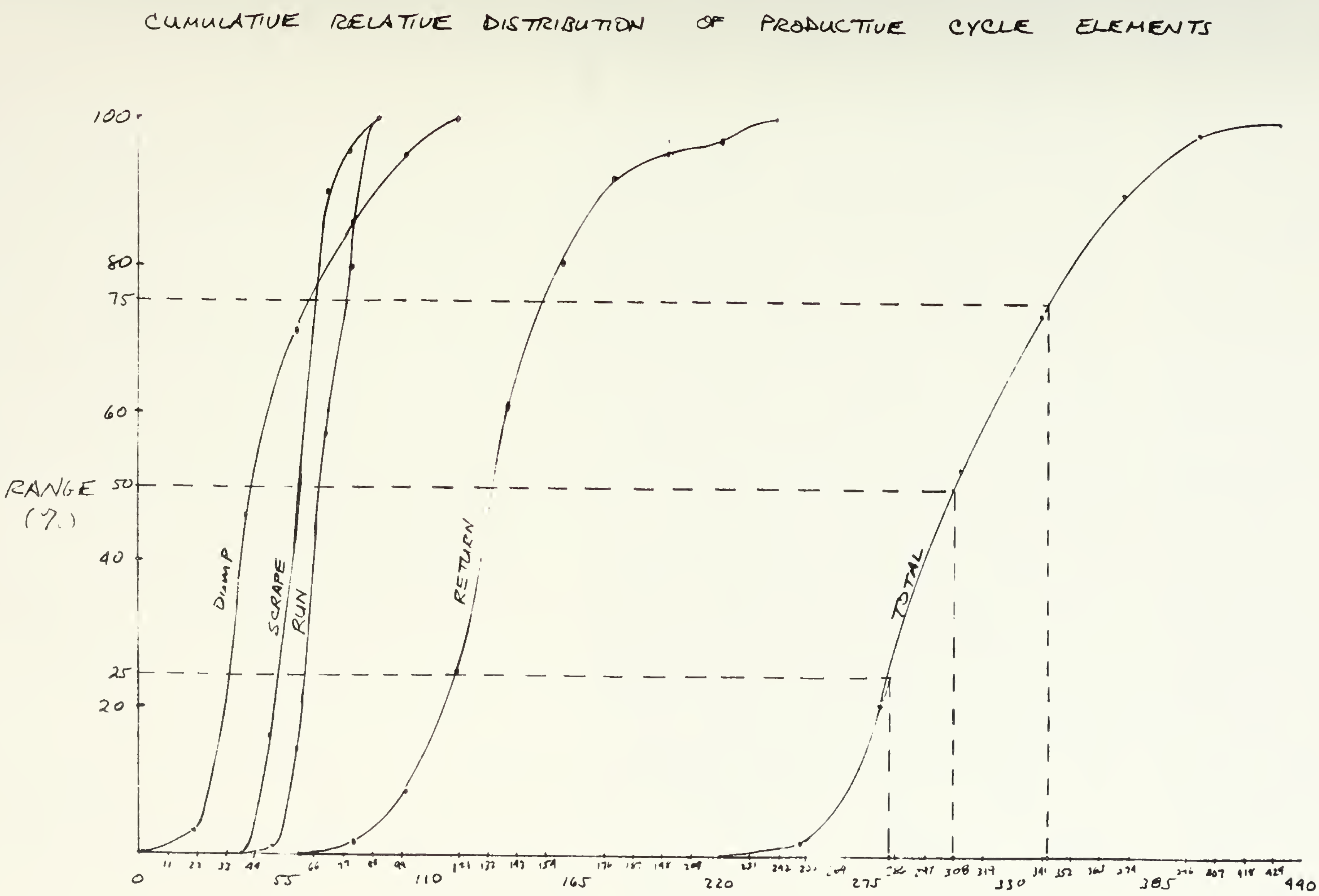


Figure 7. Cycle element time (seconds).

scrape element could be accurately recorded. Likewise, the start of the run element was apparent. The run took the scraper to a waste area approximately five hundred feet away. At that distance, the raising and lowering of the gate was obvious, and so then was the run stop-time/dump start-time. However, since the gate was not always lowered immediately upon completion of the dumping, it was not an accurate indicator of the dump stop-time/return start-time. Consequently, those last two cycles had a wider dispersion.

The resultant numbers and figures may be used for different purposes. The mean values of the element times and cycle times are useful in determining the percentages of the total time available taken up by each element. In a repetitive operation lasting for several days, knowledge of the total cycle time and the average payload of the scraper enables the estimator to predict the progress of work. The magnitude of the standard deviation (assuming accurate observations) is an indication of the control existing in an operation. A large standard deviation indicates a lack of control. The amount of delay time is important. Minutes of delay per minutes of work gives the contractor an indication of how much available time is being used for work. The amount of delay caused by minor equipment breakdowns may, if it rises above a certain level set by the contractor, indicate a need for an increased preventive maintenance program. In addition, such data recorded early in the operation gives the contractor a norm by which to measure improvement throughout the project.

WORK SAMPLING STUDY OF FINE-GRADING OPERATION

FINE GRADING WITH CATERPILLAR D3B DOZER

This work sampling study was performed on Monday morning, July 23. Fine grading was the only operation in progress at this time, and was composed of the following elements: 1) fine grading with a CAT D3B dozer, 2) measuring grade elevation, and 3) removing excess dirt from the area with a CAT 631B scraper. The measuring consisted of one crew member stretching a string across the track between two grade stakes while another measured the depth of the grade with a 6' folding rule. The depth was checked at several points across the track using the string for a reference plane. The scraper was used to carry away dirt as often as necessary to keep the dozer from building up any significant piles.

Before the work sampling was begun, work category definitions and activity classifications were established. Three categories were defined as follows: Effective Work--work which directly served to accomplish the goal of the operation; Essential Contributory Work--work which was required but which did not directly further the progress; and Ineffective Work--activity (or inactivity) which in no way assisted in the accomplishment of the task. Grading with the dozer and operating the scraper were the only two activities classified as Effective Work. Measuring grade elevation and holding the string were classified as Essential Contributory Work. The following activities were classified as Ineffective Work: standing/waiting, no contact (absence from the work site), idle (manned) dozer, discussion among workers, discussion with the inspector, idle (manned) scraper, backing dozer.

During the period of observation, 100 samples were taken at regular intervals. Taking a sample consisted of determining and recording the instantaneous activity of each of the three crew members. In total, there were 300 observations recorded (100 observations of each of the three crew members). It soon became apparent that, compared to the dozer operator, the other two crew members were virtually inactive. As a result, it was assumed that one-third of the crew members were doing effective work at any instant. In order to determine the number of observations needed to ensure a 90% confidence level with a limit of error of ± 10% (i.e., to be able to determine

the percentage of crew members within 10% of the actual percentage, 90% of the time, doing effective work) the following formula was used:

$$n = \frac{Z^2_{\alpha/2}\ (P)(1 - P)}{E^2_{max}}$$

where $Z_{\alpha/2}$ was found to be the value in a standard normal distribution table corresponding to a confidence level of 90%. The number of observations required was then

$$n = \frac{(1.645)^2(.33)(.67)}{(.10)^2} = 60$$

An implicit assumption was made, and remains to be verified, that the distribution of crew members working can be represented by a standard normal distribution. Since each sample consisted of three observations, only twenty of the 100 samples were required to meet the 90% confidence level. The twenty samples were extracted from the data base through the use of a random number table.

Table 7 presents the sampling data. It shows how many workers were found in each category. The data from the random sampling may be used as follows. The Labor Utilization Factor (Effective Work + .25 x Essential Contributory Work) gives the contractor a rough indication of how effectively he is using his manpower resources. In this case, the LUF is .33 + .25(.03) = .34. This value tends to verify the earlier observation that only one-third of the crew members appeared to be working effectively (the dozer operator).

The data may be further analyzed. Of the sixty observations, twenty were classified under Effective Work, two under Essential Contributory Work, and thirty-eight under Ineffective Work. From these numbers, we can calculate the sample proportion of success ($\hat{p}$).

$$\hat{p} = \frac{20}{60} = 33.3\%$$

Table 7. Sample data for fine-grading crew.

Work Category	Activity	Number from Sample Date	Sub-Total	Total	%
Direct Work	Grading w/Dozer	11111111111111 11	16	20	33
	Operating Scraper	1111	4		
Essential Contributory Work	Measuring	1	1	2	3
	Holding String	1	1		
Ineffective Work	Standing/Waiting	212222222222 12	26	38	64
	No Contact	111	3		
	Idle (Manned) Dozer				
	Discussion Among Workers				
	Discussion w/ Inspector	111111	6		
	Idle (Manned) Scraper				
	Backing Dozer		3		

The proportion of success in the population (p) (all recorded data sampled) may be determined from the formula

$$p = \hat{p} \pm \underbrace{Z_{\alpha/2} \sqrt{\frac{P\ (1 - P)}{n}}}_{\text{established as 10\%}}$$

P is found to be 33.3 ± 10%. We now have a confidence interval (C.I.) of $23.3 < p < 43.3$ at a 90% confidence level. That is, 90% of the time, the actual proportion of crew members doing effective work is between 23.3 and 43.3%.

If p is taken to be 33.3, a Frequency Histogram of Work Sampling Data results from the following probability calculations.

The probability of finding no crew members doing effective work:

$$b(0;\ 3,\ 33.3) = \frac{3!}{0!\ (3 - 0)!} (.333)^{0}\ (.333)^{3-0} = 3.7\%$$

The probability of finding one crew member doing effective work:

$$b(1;\ 3,\ 33.3) = \frac{3!}{1!\ (3 - 1)!} (.333)^{1}\ (.333)^{3-1} = 11\%$$

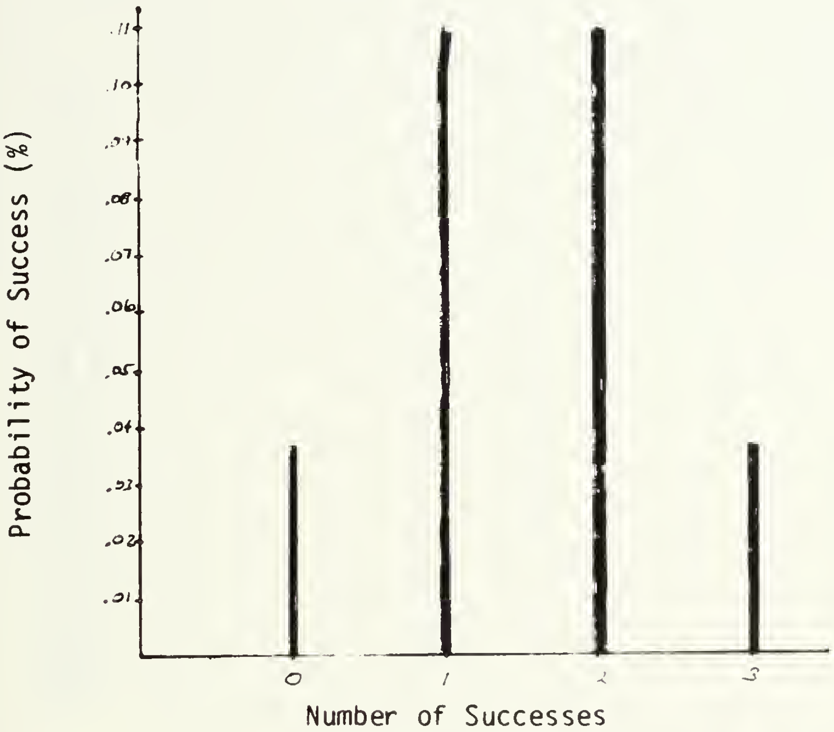
The probability of finding two crew members doing effective work:

$$b(2;\ 3,\ 33.3) = \frac{3!}{2!\ (3 - 2)!} (.333)^{2}\ (.333)^{3-2} = 11\%$$

The probability of finding three crew members doing effective work:

$$b(3;\ 3,\ 33.3) = \frac{3!}{3!\ (3 - 3)!} (.333)^{3}\ (.333)^{3-3} = 3.7\%$$

Frequency Histogram of Work Sampling Data--where Number of Successes is the number of crew members doing effective work.



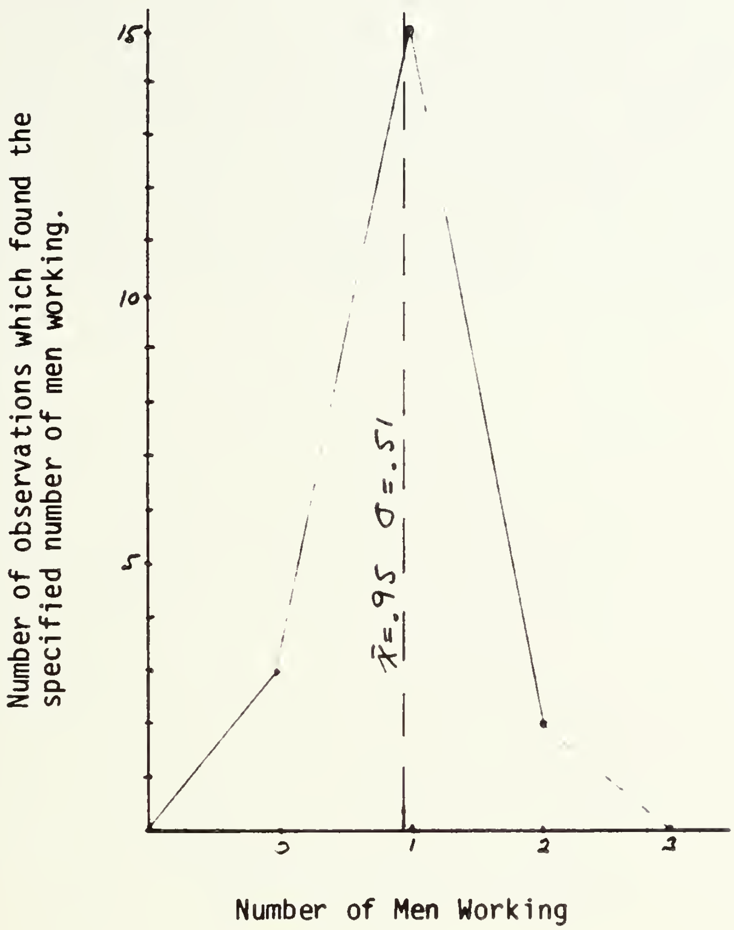
Looking at the data from a binominal standpoint, we can plot an Absolute Frequency Polygon. Table 8 shows the data from the twenty samples divided into two categories: Effective Work and Other.

Table 8. Work sampling data.

Sample Number	Effective Work	Other	Sample Number	Effective Work	Other
1	1	2	11	1	2
2	0	3	12	1	2
3	1	2	13	1	2
4	1	2	14	1	2
5	0	2	15	0	3
6	1	3	16	1	2
7	1	2	17	2	1
8	1	2	18	1	2
9	1	2	19	2	1
10	1	2	20	1	2

The data have a mean ($\overline{x}$) of .95 with a standard deviation (σ) of .51.

The Absolute Frequency Polygon shown below results.



The shape of the polygon suggests that the assumption that the sampled data could be represented by a Standard Normal Distribution is correct.

All of this data manipulation is worth little if it does not lead to a conclusion concerning the contractor's effectiveness in this particular segment of the project. The on-site observation that only one of the three crew members was working effectively, the calculated Labor Utilization Factor of 34%, the Frequency Histogram which shows the probability of finding various numbers of crew members working, and the Frequency Polygon which shows that, in 15 of the 20 observations, only one crew member was working effectively, all indicate a possible misuse of manpower resources by the contractor. The party funding this operation finds itself paying $3 for every $1 of effective work. It is a recognized fact that not all work on a project contributes directly to the accomplishment of the project, but must, nonetheless, be

performed. However, responsible management and supervision can, in many cases, eliminate excessive wasted time. In this case, the crew member who operated the scraper and held the string for the surveyor could have been eliminated. The surveyor could have tied the string to the grade stakes at each side of the track before checking elevations. Considering the infrequent use of the scraper in this operation, and the proximity of the waste area to the track, the dozer operator could have also operated the scraper without significantly increasing the length of the job. The resultant savings, though probably not a full one-third, would have been significant.

WORK SAMPLING STUDY OF PIPE-LAYING OPERATION

WORK SAMPLING STUDY OF PIPE-LAYING OPERATION

A work sampling study was performed on the pipe-laying operation which occurred on Thursday, 19 July. The operation involved digging a trench approximately three feet in depth across a 35' wide section of clay track with sloped shoulders. The cross-pipe, intended for the drainage of rain water from the high side of the track to the low side, was to be installed at approximately the 950' mark. Besides digging the trench, the three-man crew had to shape the bottom of the trench to cradle the ten four-foot sections of 21" concrete pipe, compact the bottom of the trench with a gas-powered compactor, bring the sections of pipe from the laydown area, set the sections of pipe in the trench (ensuring proper joint and alignment), and backfill with 2B gravel. The crew had apparently been given one full day to complete the task, and seemed to make every effort to ensure that a full day was required.

As with any work sampling study, work categories and activity classifications were first established. Three categories were defined: Effective Work--work directly related to the accomplishment of the task; Essential Contributory Work--work performed to provide for the accomplishment of the task, while not being directly related to it; and Ineffective Work--activity, or inactivity, which did not lead to the accomplishment of the task. Activities which were classified as Effective Work are: digging with the backhoe or shovel, setting pipe into the trench, packing dirt around the side of the pipe, operating the compactor, lifting pipe sections with the backhoe, maneuvering the backhoe, cleaning dirt off the pipe ends to ensure proper joint, and aligning pipe sections. Essential Contributory Work consisted of measuring (checking the depth of the trench and the alignment of the pipe sections), and attaching the pipe-hoist rig (either to the backhoe or to a section of pipe). The activities classified as Ineffective Work were: waiting (for an event to occur), no contact (absence from the work site), break (short duration, sitting, relaxing, conversing with other crew members, observing), and idleness (inactivity, regardless of reason).

A one and one-half hour observation time produced a data base of 145 samples. With each sample consisting of an observation of the activity of

each of the three crew members, the result was a compilation of 435 observations.

During the recording segment, it appeared as though, at best, only one of the three crew members was working effectively at any one time. Consequently, a category proportion (p) of .33 was assumed. In order to determine the number of observations required to yield a result satisfying a 90% Confidence Level with Limit of Error of ± 10%, the following formula was used.

$$n = \frac{Z^2_{\alpha/2}\,(P)(1 - P)}{E^2_{max}}$$

where $Z_{\alpha/2}$ was taken from areas under a Standard Normal Distribution. The value of n was determined to be

$$n = \frac{(1.645)^2(.33)(.67)}{(.10)^2} = 60$$

For the three-man crew, this meant that 20 samples were required. A random number table was used to select the 20 samples. The results are shown in Table 9.

The Labor Utilization Factor, a rough indication of how effectively the contractor is using his manpower may be determined by adding the percentage of Effective Work to 25% of the percentage of Essential Contributory Work. In this case, LUF = .37 + .25(.03) = .38 (a low value).

Of the 60 observations in this data subset, 27 were classified as Effective Work. The sample proportion of success (p) is then 27/60 or 45% (higher than the assumed p of 33%). The calculated proportion of success in the population (p) may now be found with the formula

$$p = \hat{p} \pm \underbrace{Z_{\alpha/2}\sqrt{\frac{P\,(1 - P)}{n}}}_{\text{established as 10\%}}$$

Table 9. Sample data for pipe-laying crew.

Work Category	Activity	Number from Sample Data	Sub-Total	Total	%
Effective Work	Digging with Backhoe	1	1	22	37
	Operating Compactor	1	1		
	Digging w/Shovel	2122	7		
	Lifting Pipe	1	1		
	Setting Pipe	12	3		
	Maneuvering Backhoe	111111111	9		
	Cleaning Pipe				
	Aligning Pipe				
	Packing Dirt Around Scale of Pipe				
Essential Contributory Work	Measuring	11	2	2	3
	Attaching Pipe-Hoist Rig				
Ineffective Work	No Contact			36	60
	Break	1122222222 211111331	32		
	Idleness	112	4		
	Waiting				

p is therefore 45 ± 10%. The confidence interval is $35 < p < 55$ at a 90% confidence level. What these numbers tell us is that, from the 60 observations analyzed, we can conclude that the percentage of crew members working effectively on the operation is between 35% and 55%, 90% of the time.

If p is taken to be 45, a Frequency Histogram results from the following probability calculations.

The probability of finding no laborers doing effective work:

$$b(0;\ 3,\ 45.0) = \frac{3!}{0!\ (3 - 0)!}\ (.45)^{0}\ (.45)^{3-0} = 9\%$$

The probability of finding one laborer doing effective work:

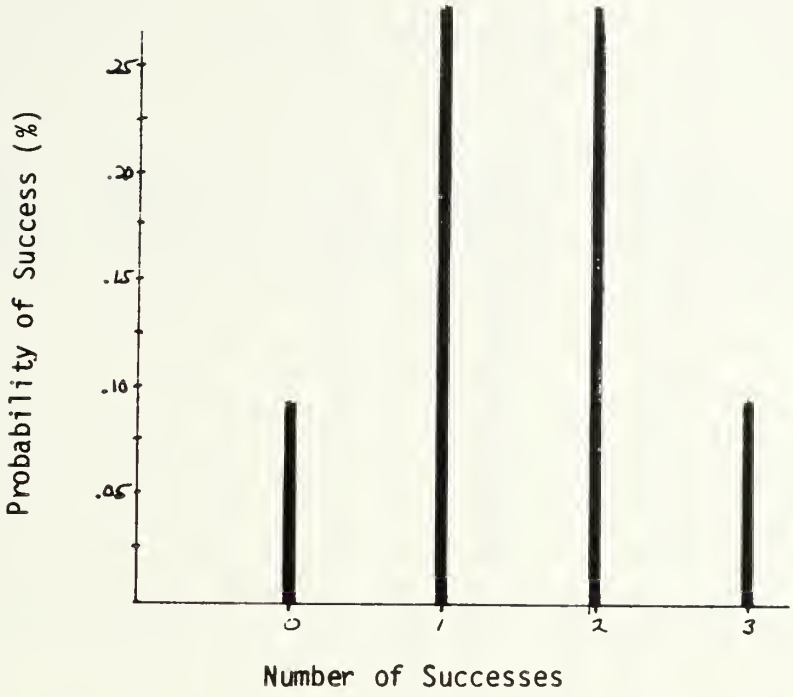
$$b(1;\ 3,\ 45.0) = \frac{3!}{1!\ (3 - 1)!}\ (.45)^{1}\ (.45)^{3-1} = 27\%$$

The probability of finding two laborers doing effective work:

$$b(2;\ 3,\ 45.0) = \frac{3!}{2!\ (3 - 2)!}\ (.45)^{2}\ (.45)^{3-2} = 27\%$$

The probability of finding three laborers doing effective work:

$$b(3;\ 3,\ 45.0) = \frac{3!}{3!\ (3 - 3)!}\ (.45)^{3}\ (.45)^{3-3} = 9\%$$



The Histogram indicates that the probability of finding none or three of the crew members working is low, while the probability of finding one or two of the crew members is higher (though not high-only 27%).

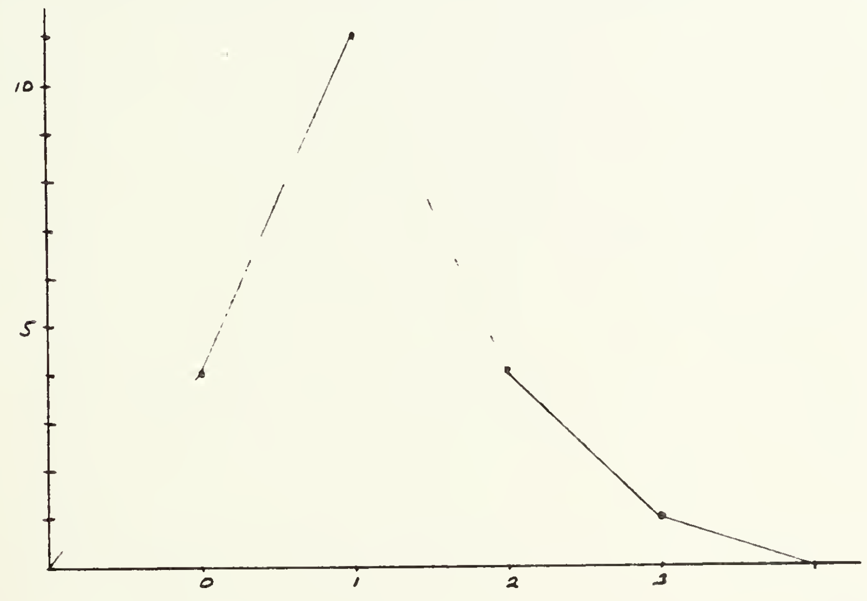
The data are now arranged and presented in a different manner. Table 10 shows the 60 observations arranged in two categories: Effective Work and Other. The calculations yield an average of approximately one of the three crew members doing effective work at any instant of observation. The Absolute Frequency Polygon shows what has been tacitly assumed from the beginning, that the distribution of data can be reasonably well represented by a standard normal distribution.

The results of the analysis, though perhaps not entirely precise (a 90% Confidence Level with a Limit of Error of ± 10%), can lead to a few general comments. It is obvious that there was a lot of "standing around" time. In fact, during the observation period, when one crew member, reclined in the seat of the backhoe, said "You guys let me know when it's time for a break," the responses from other crew members and an inspector were, "You've been on a break since you got out here," and "Working at this pace, you guys don't need a break." Reviewing the results of the analysis and the on-site impressions, it appears that the job could have been performed 1) in half the time allotted, or 2) by a smaller crew (2 men instead of 3).

Table 10. Data set #1.

Sample Number	Effective Work	Other	Sample Number	Effective Work	Other
1	3	0	11	1	2
2	2	1	12	1	2
3	1	2	13	1	2
4	1	2	14	2	1
5	1	2	15	0	3
6	1	2	16	2	1
7	1	2	17	2	1
8	1	2	18	0	3
9	1	2	19	0	3
10	1	2	20	0	3

Number of observations which found the specified number of men working.



Number of men doing effective work

SUMMARY

The construction of the Truck Arrester Bed Research Facility, begun in June, was completed in August 1984. Although the contractor's original estimate of the time required was about four weeks, poor weather conditions and competing manpower and equipment demands dragged out the project.

During the course of the project, a few instances were found in which it appeared that manpower and time were being used somewhat inefficiently. However, on a construction project, appearances can be deceiving. What seems apparent in desk-top analyses is not always practical in the field. In any event, the contractor's actions were well-executed and well-sequenced. The contractor remained flexible and cooperative and altered his actions to suit the needs of the Pennsylvania Transportation Institute, and offered several suggestions to improve the quality of the final product. The result is a well-constructed facility for research into the mechanism of stopping runaway trucks.

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